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Seismic Behaviors Estimation of the Shallow and Deep Soil Layers Using Microtremor Recording and EGF Technique in Yogyakarta City, Central Java Island

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Abstract

The technique using microtremor measurements are cost-effective tools that rapidly acquire high resolution sedimentary layer information over a large area about site response, sedimentary thickness, and average S-wave velocity structures from the secondary drilling stations. In 2012, the 274 stations of single microtremor recording were conducted to the main path of NS and EW of the research area. Microtremors were recorded with 3-components by using a model of Mitutoyo-GPL-6A3P and processed by the horizontal-to-vertical (H/V) spectral ratio technique which was used by BIDO software. The results show that the seismic behaviors in Yogyakarta City vary significantly: both of T_s and T_d spans 0.10-1.00 sec and 0.15-4.00 sec, and the thickness of sedimentary layers ranges from a few meters to over 200 meters. Moreover, to predict the strong ground motion it was used the Empirical Green's Function technique (EGF) formulated by Irikura[1,2], based on scaling law of fault parameters for large and small events and the ω^2 source spectra. The NS, EW and UD components of synthetic acceleration wave form or Peak Ground Acceleration (PGA) are calculated 392.30, 484.20 and 236.40 cm/s^2 by the EGF method respectively and the Fourier Spectrum is represented the three components by the target event and subevents for the studied area. Finally, this paper evaluates the applicability of the different techniques for seismic behaviors estimation from the H/V spectral ratio of microtremor recordings and EGF method based on the Opak River Fault.

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***Keywords*:** Seismic Behaviors; Microtremor; Shorter and Longer Predominant Periods; Sediment Thickness; EGF Technique; Yogyakarta City

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1. Introduction

Yogyakarta city is expected to exhibit strong site effects due to its irregular topography and also to its surface geology which presents very thick young volcanic deposit layers of Merapi volcano. To test the feasibility of the Nakamura method[3] for the characterization of the deep Quaternary layers in the Yogyakarta city, the single microtremor measurements were performed in the down town area on the Yogyakarta depression. The predominant periods obtained with the Nakamura method were correlated with the thickness of the Quaternary deposits showing, again, a good agreement.

Earthquake hazard and risk in Indonesia has been conspicuous in recent years, dramatically brought into the public eye by the great tsunami earthquake (Aceh 2004, 9.0 M_w), collapse of public buildings and hotels (Padang 2009, 7.5 M_w) and by extensive destruction of private dwellings caused by the relatively smaller magnitude Bantul, Yogyakarta 2006 (6.3 M_w) earthquake. The 2006 Bantul earthquake occurred on 27th May at 05.33 a.m. (local time or 22.54 on the 26th UTC). Dwelling collapse rates reached 60% with over 60,000 houses destroyed, 5,700 fatalities and 37,000 injured, over 200,000 homeless and heavy damage at more than 300 school buildings. Yogyakarta has a history of strong earthquakes, for example, 10 June 1867, 27 September 1937 and 13 March 1981. It is also reported that a devastating eruption of Merapi was induced in 1006 by an earthquake similar to that of 2006. The Yogyakarta community is vulnerable to major geophysical hazards and a vital step towards community empowerment and resilience is the identification of disaster prone areas. This earthquake underlines the need for better understanding and simple display of the factors that may influence variations in strong ground shaking.

The Yogyakarta city, the target area for this study, is an important factor for the prevention or mitigation of earthquake disasters. This concentration of damage is thought by the characteristics of the earthquake strong motion and by the local subsurface structure of the Yogyakarta city. The observations of microtremor and the Empirical Green's Function Technique (EGF) have been carried out in this area. The purpose of our study was to determine the subsurface and bedrock structures of the Yogyakarta city and predict the strong ground motion by the use of the single microtremor observations and EGF technique based on the Opak River Fault.

2. Historical Seismicity and Geological Settings

Earthquake strong ground shaking hazard is influenced by many factors. These obviously include earthquake size and proximity but also include more subtle influences, for example, predominant rock type, thickness of sedimentary cover and water table depth. These latter influences provide a means to map spatial variation of intensity enhancement attributable to spatially known and fixed geological features. The existing detailed geological mapping of Yogyakarta Special Province (YSP) is used to identify ten characteristic geological formations and further lithologic units. The early Miocene Nglanggran Formation (andesitic intrusion and basaltic lava) has high S-wave velocity and density, hence highest seismic impedance of the characteristic geological formations is adopted as the reference unit.

The area of study under consideration is Yogyakarta city where is located in the center of the Yogyakarta Basin and has a population of 388.088 and the density of 12.000/km^2. The Opak River fault, which runs NE-SW of study area, is a major cause of many ground motions in this area. Most of the area is occupied by the young volcanic deposit of Merapi volcano sediments of Quaternary age which are derived from the Merapi active volcano and including sand, silt, clay, volcanic ash, tuff and agglomerate sediments.

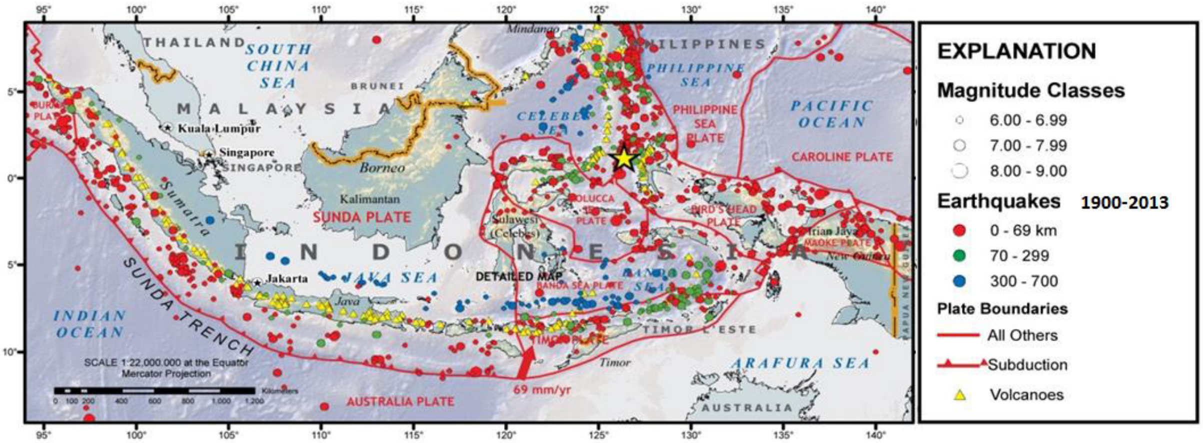

Fig. 1. Historical seismicity and geological setting in Indonesia region

Along the Java trench, the Australian plate is subducting beneath the Java continental crust (Sunda plate) with a convergence rate of 6.7±0.7 cm/year in a direction approximately orthogonal to the trench toward Java[5,6]. The Australian plate dips north-northeastward from the Java trench, and the depth of the plate interface is 100–200 km beneath the island of Java[7] as shown in Figure 1. The May 2006 earthquake occurred at a shallow depth in the overriding Sunda plate, well above the Australian plate; thus, the earthquake was not directly associated with the subduction regime, but rather occurred on shallower faults that were stressed by the deeper subduction mechanism. Wagner *et al*.,[7] interpreted the 2006 earthquake to have occurred at the edge of the weakened (fractured) area between two forearc blocks. They further argued that a change in subducting plate interface angle 150 km landward from the trench causes a northward pushing and stress accumulation in the overriding plate where the 2006 earthquake occurred. Therefore, this geological setting should be seismogenically active. The fault bounds a region covered by young volcanic deposits[8,9]. The deposited clastic material is generally soft, consisting of breccia and pyroclastic deposits reaching a thickness of 150–200 m [8]. Walter *et al*.,[10] argued that the young volcanic deposits filled the graben bounded by the Opak River fault and amplified the ground motion to cause the disastrous damage along the Opak River fault in the 2006 event. Figure 2 displays the historical seismic events around Yogyakarta in central Java.

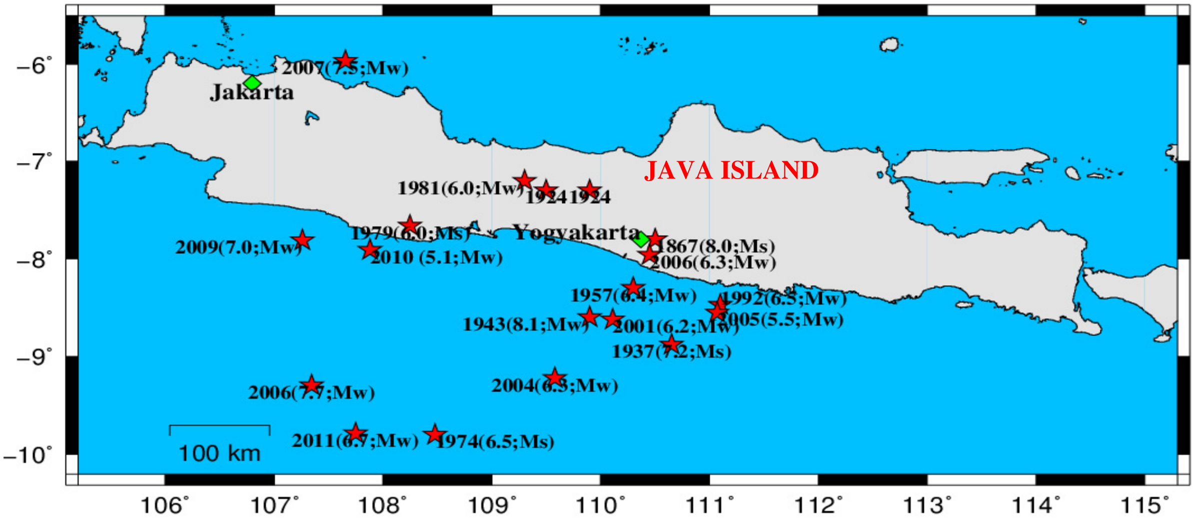

Fig. 2. The historical seismic events around Yogyakarta in central Java

3. Methodology

3.1. Characteristics of Microtremors

The HVSR technique is a very useful tool for subsurface soil structure and site response studies. The method is especially recommended in areas of low and moderate seismicity, owing to the lack of significant earthquake recordings. Microtremor measurements can be used to determine the dynamic properties of a site and, hence, can be used for seismic microzonation purpose. Microtremor method measures ambient vibrations in the order of microns present in the ground[3]. The observation of these microtremors can be used to determine the predominant period of vibration of a station[11,12].

Besides, the 274 stations of the single microtremors observations in Yogyakarta City and the topography map of Yogyakarta area show in the Figure 3. During the daytime, the observations were performed by using a microtremor device which is model of Mitutoyo-GPL-6A3P and serial No. 0418707 as shown in Figure 4 (a) and (b). A single seismic location was carried out for the microtremor measurements. It was consisted of a short-period, three-component seismometer with natural period of one second, a 24-bit A/D converter with GPS time, sampling each channel at 100, and a laptop computer to control the system and store the data. The microtremors observations were recorded with a sampling rate of 100 H_z at each site.

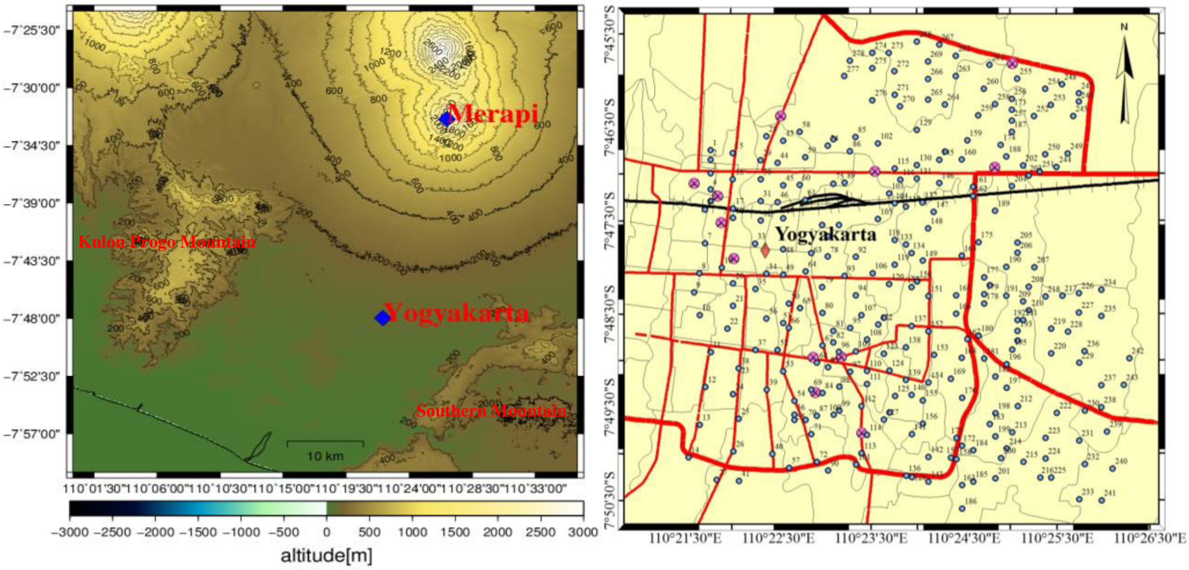

Fig. 3. Topography of Yogyakarta area and the distributions of the single microtremor observations with drilling stations

Fig. 4. The microtremor device of (a) external view and (b) internal view (model of Mitutoyo GPL 6A3P and serial No. 0418707)

3.2. Procedure and Results

A full microtremor record can be expressed by one vertical and two horizontal components. The analysis was conducted using the recorded microtremor. The ratio between the Fourier amplitude spectra of the horizontal (H) to vertical (V) components of ambient noise vibrations recorded at one single station. The peak period of the HVSR is conducted to correspond to the resonant period of the site.

The procedure generally used to calculate the HVSR consists in the application of Equation (1). It performs the average amplitude spectra of the three components of motion. This H/V spectral ratio method determines the shape of the Fast Fourier spectrum[13]:

$$HVSR = \frac{\sqrt{F_{NSi}(\omega)^2 + F_{EWi}(\omega)^2}}{F_{UDi}(\omega)^2} \tag{1}$$

where $F_{NSi}(\omega)$, $F_{EWi}(\omega)$ and $F_{UDi}(\omega)$ denote the Fourier amplitude of the NS, EW and UD components of each interval, respectively, and ω is the frequency. The BIDO software can be used to calculate the H/V spectral ratio and to identify properties of surface waves that travel on the ground surface by analyzing circular-array records of microtremors (ambient vibrations; bidô in Japanese). Figure 5 (a) and (b) display the example of microtremor record: north-south, east-west and up-down components and its related the average frequency with standard deviation of H/V curves.

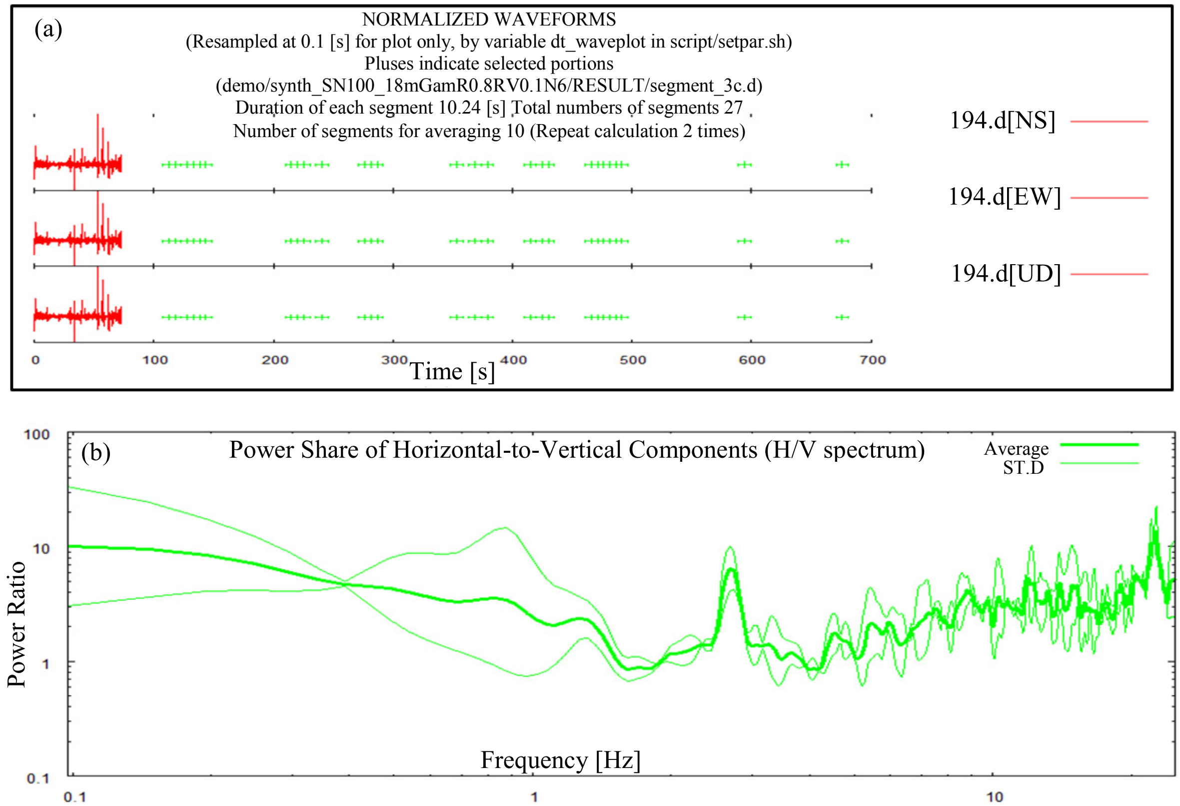

Fig. 5. Example of microtremor record: (a) the north-south, east-west and up-down components and (b) its related the average frequency with standard deviation of H/V spectrum

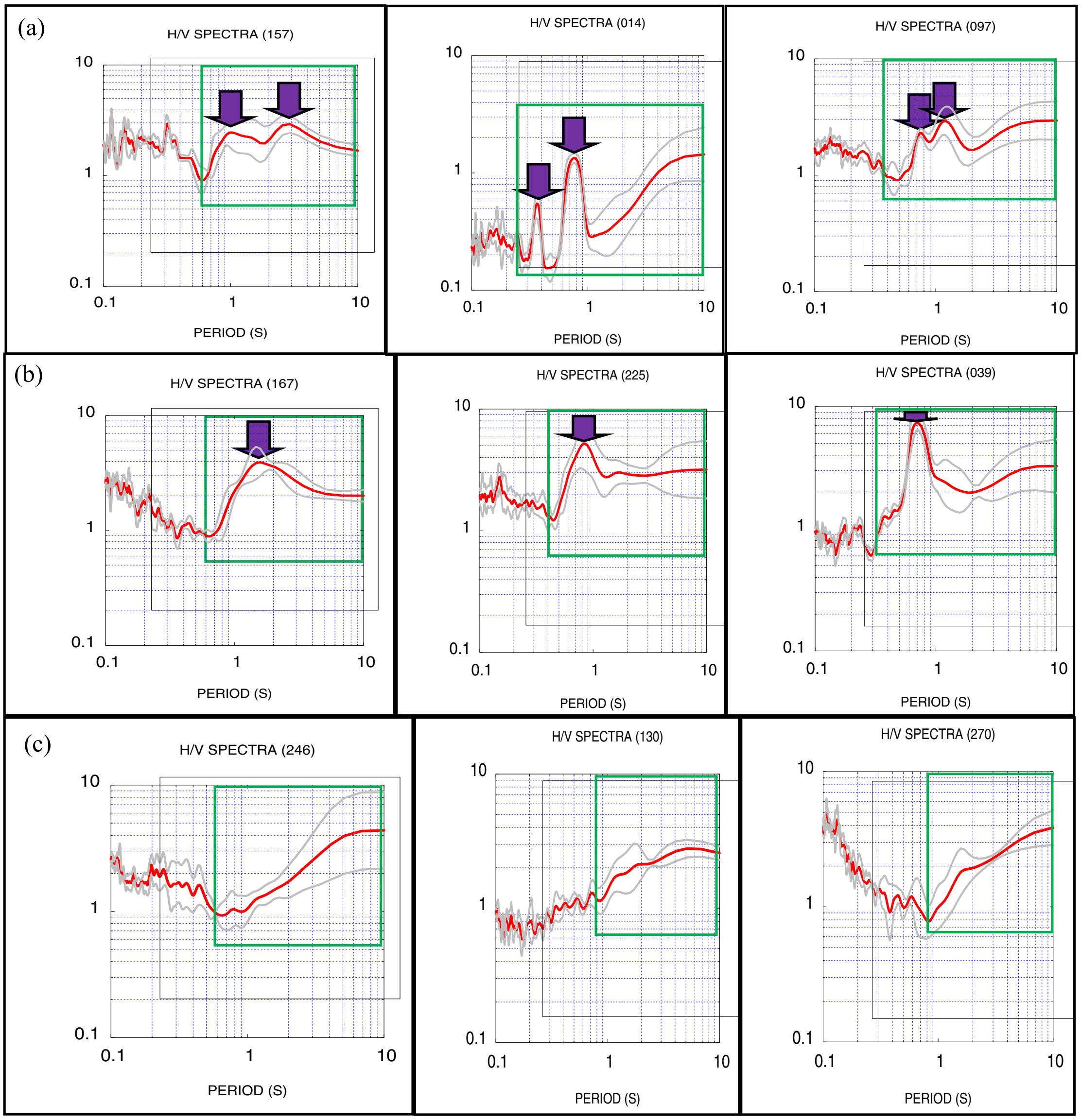

Fig. 6. Typical examples of (a) the two distinct peaks, (b) a single clear peak and (c) without clear peaks of the H/V spectrum ratio and standard deviations

To be equivalent to the predominant period of the ground, the predominant period of an H/V spectrum is determined directly beneath the site. At each station in the study area, the H/V spectra were performed. According to the shape of the spectra, the calculations of H/V spectra were classified into three categories[14].

- Category A: the two distinct peaks (Figure 6 (a))
- Category B: a single clear peak (Figure 6 (b))
- Category C: without clear peaks (Figure 6 (c))

Although the shear wave velocity is quite different, the clear peaks describe the characteristic of the layers. If each value of the predominant period obtained is considered to be a realization of a stochastic random field, it can be used the Ordinary Kriging technique, which is one of the interpolation techniques that considers the covariance of the random field. The presence of the single clear peak of H/V curve (Figure 6-b) is considered as an indicative of the impedance contrast between the uppermost surface soil and the underlying hard rock, where peak values are generally associated with sharp velocity contrasts[15] and is likely to amplify the ground motion. Besides, the different between the two layers is not recognized, and the effect of one layer is disappeared into that of the other layer. Figure 6 (a) illustrates two of peaks that reflect the presence of two large impedance contrasts and this could be related to the presence of an underground sloping of the interface between shallow and deep soil layers. Figure 6 (c) expresses an observation site of without clear peaks that has hard soil.

3.3. Spatial Distribution of the Shorter and Longer Predominant Periods

Yogyakarta, the smallest city in Indonesia, is located at a closely distance from seismic sources. It has a substantial risk from the earthquakes due to the ability of the underlying soft sediments to amplify ground motions in Yogyakarta Depression. It is therefore imperative to conduct a detailed seismic hazard assessment of the area. The distribution of the predominant period and the amplification rate are obtained by all measuring point data. The contour of the predominant period is also shown. When the entire of the study is analyzed, following features can be noted. In the eastern part of Yogyakarta City, there are 274 observation points which are enough to cover the research area.

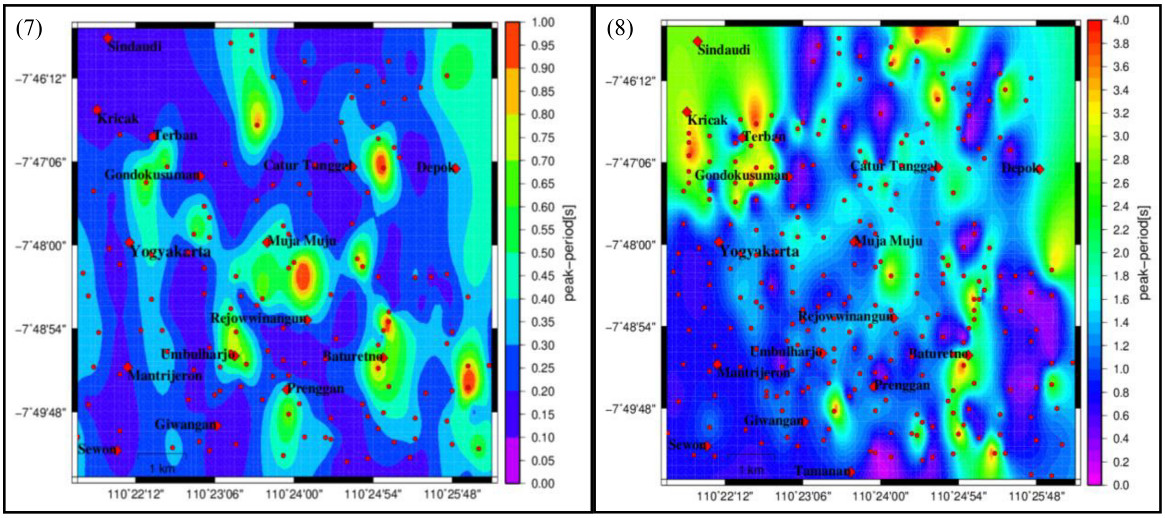

Fig. 7. Spatial distribution of the shorter predominant period (T_s) and Fig. 8. Spatial distribution of the longer predominant period (T_d)

The shorter predominant periods, T_s, is obtained from 0.1 to 1.00 sec from the single microtremor observations. The target area is less than 1.00 sec of the shorter predominant periods which relates the information of the shallow soil layer as shown in Figure 7. The shorter predominant periods at Sindaudi, Kricak, Terban, Gondokusuman, Catur Tunggal, Depok, Yogyakarta, Rejowwinangun, Mantrijeron, Giwangan and Sewon is ranging from 0.10 to 0.40 sec which means that these areas are very shallow soil layer and the rest areas are between 0.40 and 1.00 sec. It is understood that the relatively shallow soil structures can be detected from H/V spectrum of shorter period microtremor when the clear layer boundary with high impedance ratio is existed.

The longer predominant period in the research area is ranging from 0.15 to 4.00 sec as shown in Figure 8. Form the longer predominant periods, T_d, which describes the information of relatively deep sedimentary layer, a deep layer with a period of greater than 1.8 sec is observed in studied area. It is obviously observed that the area where thicker sediments show higher predominant periods. Figure 7 and 8 are displaying the distribution of the site predominant periods especially shorter and longer predominant periods were developed for the seismic microzonation purpose.

4. Estimation of Sediment Thickness or Depth of the Engineering Bedrock

The sediment thickness is determined from predominant period in the longer range of H/V spectra of microtremor measurments. Average S-wave velocity from the boring stations is roughly estimated for each soil layers. The depth of upper boundary of engineering bedrock is calculated from first predominant period (longer predominant period). The higher predominant period exists when clear impedance ratio is detected. The collection of data concerning the bedrock structure and the S-wave velocity profile is necessary for more accuracy.

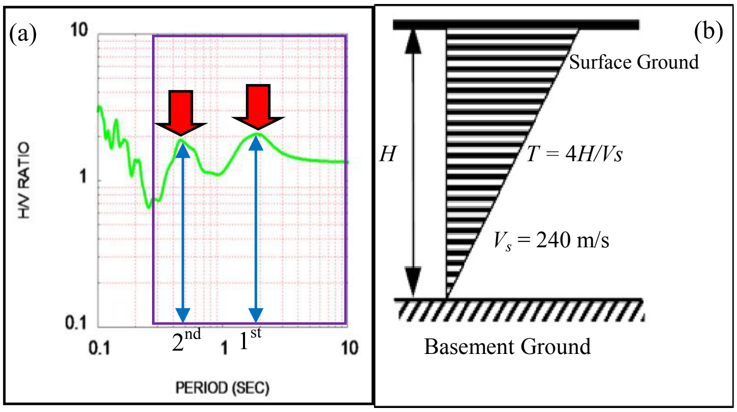

Fig. 9. Basic principle of (a) site response of H/V ratio and (b) a simple two-layer model

The peak in the predominant periods of the observed H/V spectrum could be determined by the estimated subsurface soil layers. In this study, it can be used a first peak in case of the two distinct peaks existing in the observed H/V spectra and V_S structure obtained from the secondary boring stations. The technique used was the 1/4 wavelength principle, which can approximately be extended to multi-layered media[16,17]:

$$T = 4H/V_S \tag{2}$$

where H is the sediment thickness of a layer as shown in Equation (2). In Figure 9 (a) and (b), it is a good correlation between the sediment thickness and the longer predominant period (1st peak).

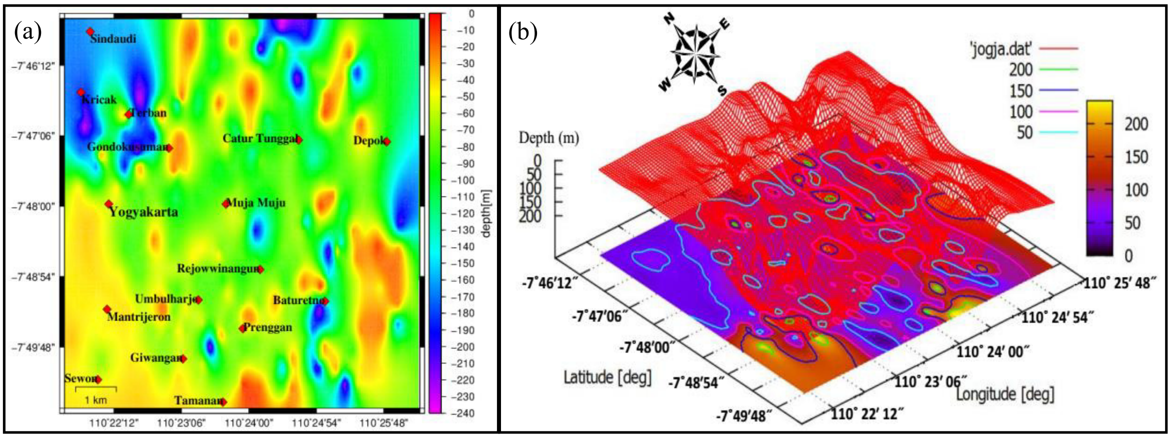

Fig. 10. (a) Spatial distribution of the sediment thickness and (b) three-dimensional shape of the estimated subsurface soil layer

The thick and loose sediments are observed in the almost of the whole area (>80 m) and the high amplification and strong ground motion can occur in these area as shown in Figure 10 (a). Sindaudi, Kricak, Terban, Gondokusuman and north part of area are included in very thick sediment zones (>180 m).The thickness of sediments in Catur Tunggal, Depok, Yogyakarta, Muja Muju, Rejowwinangun and Umbulharjo are over 60 m and medium to high amplification can be expected. The shallow sediments are investigated in north-west of Mantrijeron, Sewon, Tamanan, east of Baturetno and some part of north of the area where can be regarded as low amplification zones.

Figure 10 (b) displays the three-dimensional shape of the estimated subsurface layer in Yogyakarta City. The deep soil layer can be seen the greater than 60 m which derived from the longer predominant periods and S-wave velocity. It is clearly noticed that the almost of the studied area can be found the less than 100 m depth for the deep soil layer. In the research area, the boundary depth was around 200-220 m to the bedrock which appeared a little bit deep. Analyzing to the microtremor sites, although the elevation of surrounding area is almost at the same level about 150 m, a gentle change in sedimentary layers can be observed.

5. Estimation of Strong Ground Motion in Broad-Frequency Band Based on a Seismic Source Scaling Model and an Empirical Green's Function Technique (EGF)

There are three kinds of techniques to simulate the strong ground motion and these are: (1) The composite source modeling technique (2) The method of Empirical Green's Function (EGF) (3) The method of stochastic simulation of high-frequency ground motion. Figure 11 displays parameterization of the seismic source with the observation area, Opak River Falut and rupture starting point for the simulations of strong ground motion.

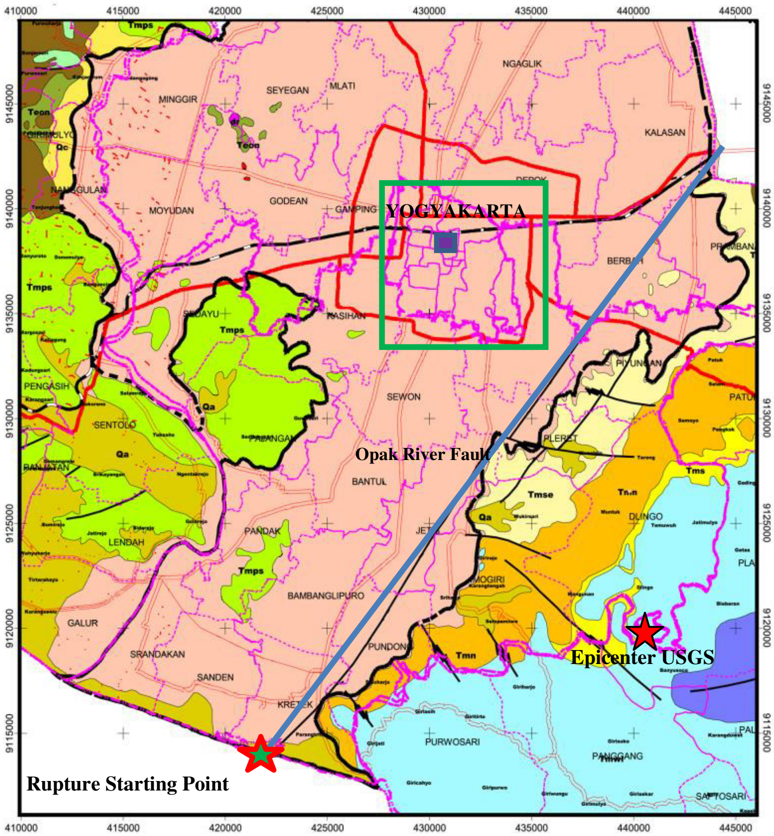

Fig. 11. Parameterization of the seismic source with the observation area, Opak River Fault and rupture starting point for the simulations of strong ground motion

As an empirical Green's function, a useful approach for this study is to estimate strong ground motion for a large earthquake using the record of small earthquakes. The main idea of the empirical Green's function (EGF) method is that the small events have already included the properties of the propagation path and local site effects. EGF method can provide realistic ground motion including high-frequency component.

In the presented work it was used the EGF method formulated by Irikura[1,2], based on scaling law of fault parameters for large and small events[18] and the ω^2 source spectra[19,20]. The waveform for a large event is synthesized by summing the records of small events with corrections for the difference in the slip velocity time.

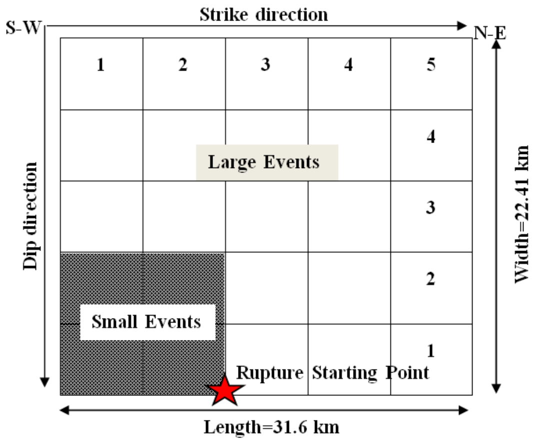

Fig. 12. Fault parameterization of the seismic source with asperity for the simulations of strong ground motion

Figure 12 displays fault parameterization of the seismic source with asperity for the simulations of strong ground motion. From the waveform simulations, they got the asperity size is about 31.6 km length in the strike direction by 22.41 km width in the dip direction. The rupture started at the left-bottom of the asperity and extended radially to the right-upper direction when the mainshock happened. They also mentioned the stress drop $\Delta\sigma$ and the scaling parameter N of the mainshock is M_w 6.3. Based on this source model, the synthetic waveform of the small event is selected as the input motion to simulate the mainshock record using the summation procedure of the EGF method[2].

It was introduced a generalized method for simulation strong ground motion from large earthquake by summing subevent records to follow the ω^2 law. The original idea of the method is based on a constant stress parameter between the target event and subevent. It is applicable to a case where both events have a different stress drop after some manipulation. However, the simulation for a very large earthquake from a small event with this method has inevitably some deficiencies of spectral amplitudes in the intermediate frequency range deviating from the ω^2 model, although the high and low frequency motions match the scaling. It shows successful simulations for intermediate-sized earthquakes (M_w 6.3) as an Empirical Green's Function.

To test this method it has been used the strong motion data of the Yogyakarta earthquake of 27th May 2006. The source of this earthquake is modelled by a simple rectangular rupture of size 5 × 5, burried at a depth of 18.0 km in a multilayered earth model. This rupture plane is divided into 25 rectangular subfaults of size 31.60 × 22.41 km. Strong motion records at studied area were simulated and compared with the observed records in terms of the acceleration, velocity and displacement records and their Fourier Spectrum with frequency. Table 1 shows the theoretical calculation of the source parameters for Opak River Fault and M_w 6.3 of Yogyakarta earthquake.

Table 1 Theoretical source parameters for Opak River Fault and M_w 6.3 of Yogyakarta earthquake

Source parameter	Mainshock 27/May/2006 05:54:00 a.m [Local Time]
Fault Length (km)	31.6
Fault Width (km)	22.41
Fault Area (km^2)	708.156
Fault Depth (Top) (km)	3.0
Fault Depth (Bottom) (km)	18.0
Density (t/m^3)	2.8
Shear Velocity (km/s)	3.3
Stiffness (N/m^2)	3.10E+10
Moment Magnitude (M_w)	6.3
Seismic Moment (M_o)(dyne-cm)	0.79E+25
Maximum Frequency (H_z)	10
Stress Drop ($\Delta\sigma$) (bar)	17.3
Velocity of Rupture on Fault (km/s)	2.52

5.1. *Response Analysis by Synthetic Earthquake Motion*

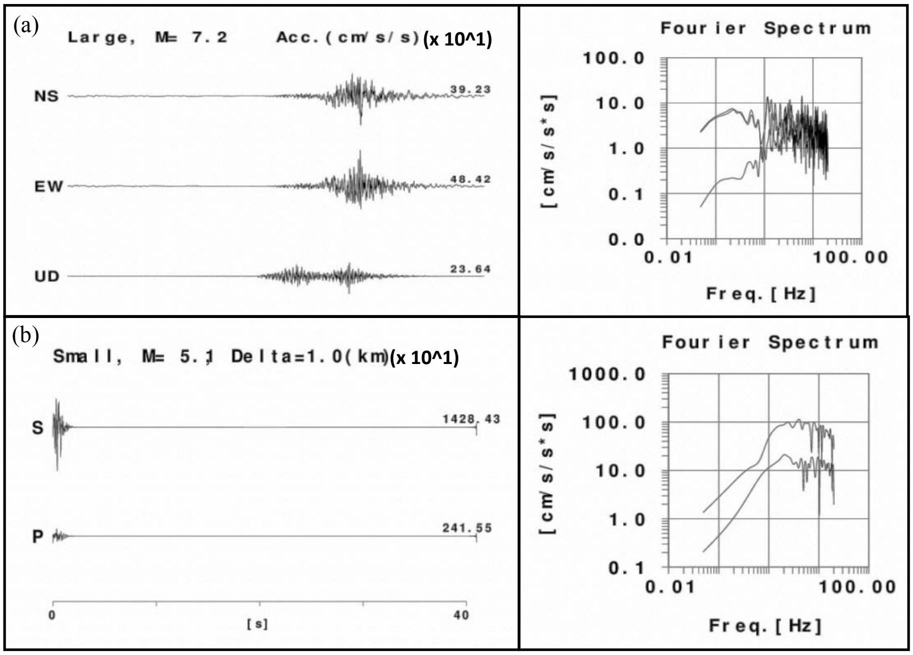

Fig. 13. (a) The time histories of the synthetic acceleration wave forms with NS, EW and UD components (in cm/sec^2) with simulated spectra (Fourier Spectrum) of a target event (b) S-wave and P-wave with simulated spectra (Fourier Spectrum) of a target subevent

As shown in Figure 13 (a), the NS, EW and UD components of synthetic acceleration wave form or PGA are calculated 392.30, 484.20 and 236.40 cm/s^2 by the EGF technique respectively and the Fourier Spectrum is represented the three components by the target event and subevents for the studied area. The acceleration induced by the synthetic wave form is a little bit high for the EW component of time history and Fourier Spectrum. Moreover, the Yogyakarta City is located on soft sediment or young volcanic deposit of Merapi volcano. Therefore, the high acceleration contents of seismic wave may be strongly amplified to the Yogyakarta City in the future earthquake.

The energy of an earthquake is released within seconds and spreads through the Earth as seismic waves. Wave velocity varies with the different wave types, and so does the damage caused at the surface. The P-wave is the fastest wave, but it usually causes less damage than the surface wave, which travels slower, makes the ground shake severely, and produces larger damage. Figure 13 (b) displays the S-wave and P-wave are 14284.30 and 2415.50 km/s with their frequency content of the Fourier Spectrum by the target subevent.

5.2 Validation for PGA with Synthetic Motion from EGF and Recorded Motion at YOGI Station

The YOGI station which is at less than 100 km from the epicenter and have relatively useable waveforms and is belong BMKG (Indonesian non-departmental government Agency for meteorology, climatology, and geophysics) and located at 7˚ 49′ S and 110˚ 18′ E. Figure 14 (a) and (b) show comparison of the synthetic acceleration wave form from the EGF calculation and observed wave form the YOGI station in Yogyakarta earthquake.

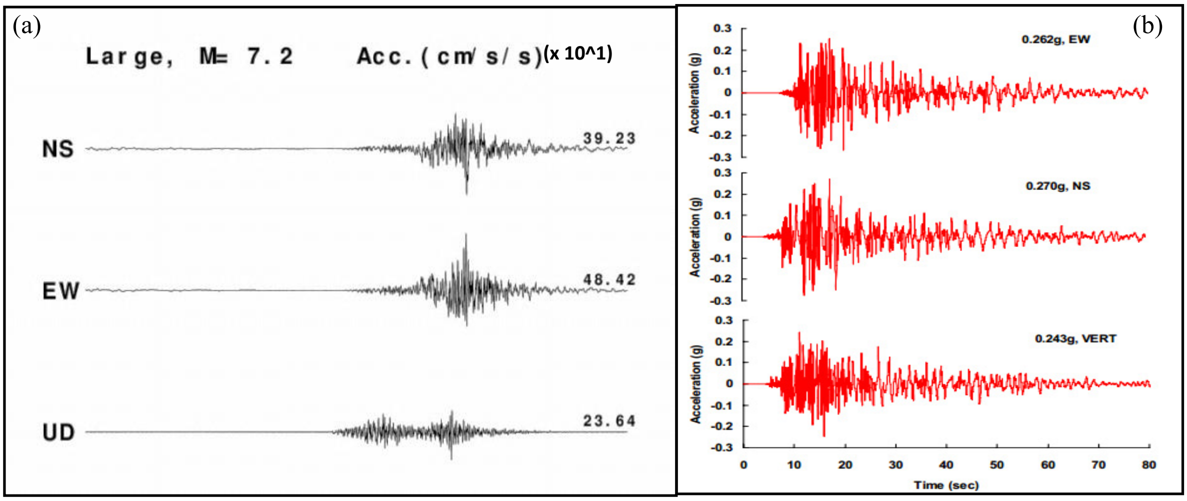

Fig. 14. Comparison of (a) the synthetic acceleration wave form from the EGF calculation and (b) observed wave form the YOGI station in Yogyakarta earthquake

The signal from YOGI is the most usable of the available records, since it is obtained from an area where significant damage has occurred. The EW component of synthetic acceleration from EGF calculation shows 0.48 g and similarly the EW component of recorded acceleration from YOGI station is 0.27 g it is noticed that synthetic acceleration is a little bit higher than the recorded acceleration but both of the value of the UD component are very similar.

The Yogyakarta earthquake was the most destructive earthquake in Java Island, with the widest zone of influence and the most serious disaster-induced losses. Therefore, it will be need to mitigate for the future strong earthquake in Yogyakarta area and to validate for PGA values derived from the microtremor observations by comparing the available seismic hazard maps and synthetic acceleration wave form. According to the different kinds of validations, it is obviously observed that the calculated PGA map show good agreements to other seismic hazard maps and damage distribution.

Conclusions

The single microtremor records can be used to obtain reliable information related with the seismic behavior of thicker young volcanic deposit layers at the research area. The agreement between experimental data and numerical calculations is also good, considering an average shear wave velocity of 240 m/s from the secondary borehole stations in the soft young volcanic deposit layers. It is possible to say that, the use of microtremor measurements seems to be very useful to estimate the site response for thicker young volcanic deposits, in terms of the shorter and longer predominant periods, contributing as a fast, simple and economic method for seismic microzonation purposes. It might also be a useful tool for geotechnical survey, to get information on the shallow and deep soil layers and the sediment thickness.

Both of shorter and longer predominant periods maps will be fundamental guidance for future housing development and new city plan and mitigation of socio-economic impacts. The buildings with the longer predominant periods (>1sec) of strong ground motion might be severely affected during future earthquakes. The results from this study well approve that the predominant period is performed the thick sediment thickness or deep sedimentary layer boundary and dominated in S-wave velocity.

It has been presented a simplified method for broad-band simulation of the strong ground motion based on the EGF method of Irikura (1986). It can be concluded that the method is effective for the prediction of parameters of the strong ground motion for large earthquakes at research area that have limited seismic observations. The result of the source scaling properties of the simulated earthquake using the empirical relations shows that it might be the strong earthquake in research area in the future.

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